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Evaluation of a New Concept for Reducing Free-Stream Turbulence in Wind Tunnels

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FOREWORD

This work is just one of many performed over the last ten years at IIT on the management and control of free-stream turbulence, as well as other flow characteristics. During some of these studies we have especially concentrated on those which are typically found in wind tunnels. This work was particularly aimed at the development of techniques for improving the flow in many existing wind tunnels, as most of them have very short or no settling chamber ahead of the contraction.

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INTRODUCTION

Most experiments conducted in wind tunnels require a low
turbulence intensity in the test section, with good spatial
uniformity of both the mean velocity and the turbulence intensity.
Recent proposed experiments, such as laminar flow control (LFC),
impose a severe restriction on the maximum allowable turbulence
level in the test section. According to Dr. W. Pfenninger, of
NASA LaRC, turbulence intensities of less than 0.1% will be required.

Due to recent work in the area of turbulence control and
management,[1,2,3] as well as on control of secondary flows in
ducts[4,5,6] this level is not unattainable under certain conditions.
Specifically, efficient compact combinations of honeycombs, grids,
screens and other flow manipulators have been developed which
lead to substantial reductions in the free-stream turbulence
levels with a minimum of power loss due to manipulator pressure
drop. The optimum arrangements depend on maximization of the
manipulator turbulence suppression functions and minimization of
their generation functions.[1,2,3] In particular, the important
role of the shear layer instabilities and the proper balance
between the different scales of the manipulator and the turbulence
are considered in the design of efficient manipulator combinations.[2,3]
In most cases, available power limitations of the facility make
the use of these combinations desirable, if not mandatory, to
achieve the required turbulence level.

However, another extremely important feature of using these
flow manipulator combinations is the provision for adequate
decay distance between manipulators as well as downstream of the
final manipulator ahead of the contraction. Unfortunately, most
wind tunnels have little, if any, settling chamber between the
turning vanes and the start of the contraction. This lack of any
appreciable settling chamber has a severe restrictive effect
on the type and number of manipulators that can be used for
improving the turbulence level, with subsequent limits on the
amount of turbulence reduction that can be accomplished. While

new wind tunnel facilities are, or should be, designed with a settling chamber long enough for proper turbulence management, and some older facilities can be modified to provide an adequate settling chamber for maximum reduction in the test section turbulence intensity, there are many wind-tunnels, especially those of large cross-sectional area, that cannot be modified. The LaRC/5m TDT is one of these tunnels.

Since new large facilities are extremely expensive, efforts are underway in several facilities to improve performance of these short settling chamber wind tunnels for present-day experiments, such as LFC. In particular, the LaRC/5m TDT was being considered as a possible facility for conducting LFC experiments. While no reliable measurements of turbulence intensity are available for the test section, realistic estimates indicate a level much higher than the 0.1% required for LFC experiments, probably 0.3 - 0.5%. These estimates are based on the turbulence decay downstream of the last set of turning vanes ahead of the contraction. This indicates the necessity of a substantial turbulence reduction in the test section with essentially no appreciable settling chamber length to allow for the flow manipulators and the turbulence decay. As one method of possibly overcoming this situation, a "new concept" honeycomb was proposed.

In the conventional method of installing honeycombs, screens and grids in the wind tunnel, the plane of the manipulator is normal to the mean flow. This results in the manipulator being closer to the turning vanes at the inside of the corner and further away at the outside of the corner. This situation is depicted in Figure 1. There is a much larger distance at the outside of the corner over which the turbulence and wakes from the turning vanes decays. From the point of view of turbulence control, this additional distance is wasted, especially in wind tunnels with little settling chamber distance. Instead of using this distance for the decay of the "uncontrolled" flow characteristics due to the turning vanes, the "new concept" honeycomb uses it for additional decay of the modified, and usually improved (i.e.,

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faster decaying and of more appropriate scales), turbulence down-stream of the manipulator. This arrangement is also depicted in Figure 1. Note that the cells of the honeycomb are still aligned with the mean flow direction, although the plane of the honeycomb is now parallel to the plane of the turning vanes at 45 degrees to the mean flow direction. For this reason the "new concept" honeycomb will also be referred to as the 45° honeycomb. Although this type of honeycomb is more expensive, there is an additional advantage in that the 45° honeycomb can be supported by the turning vanes and thus eliminates the need for a separate support structure.

In light of the totally new nature of this manipulator, several experiments were performed to evaluate the overall performance characteristics and optimize the parameters involved. Of particular interest is the relative effectiveness of the 45° honeycomb (and 45° screen combination) in comparison with the conventional honeycomb (and screen combination). The majority of the experiments were conducted to reveal the turbulence reduction mechanisms, document the effectiveness of the "new concept" honeycomb and to provide information as to whether or not the 45° honeycomb (and 45° screen combination) is a viable alternative to the conventional honeycomb (and screen).

TEST FACILITIES AND INSTRUMENTATION

In order to evaluate the proposed "new concept" 45° honeycomb-45° screen combination, a scale model of the 90° corner and turning vanes of the NASA LaRC/5m TDT was used. Based on the results of the scaling process, which will be discussed further in this section, a small open circuit wind tunnel was selected for the experiments.

Wind Tunnel Characteristics

The wind tunnel was powered by a blower which exhausted into the upstream end of its settling chamber. Velocities in excess of 75 m/sec are possible in the test section, with the lower speeds being attained by throttling the blower output. Several flow manipulators are located in the settling chamber in order to spatially uniformize the flow velocities and for turbulence control. The test section is located downstream of a 25 to 1 contraction and is assembled using various lengths of plexiglas tube of circular cross-section, 15 cm in diameter. Every section has a flange on each end, so that as many sections as desired can be bolted together to form the test section. The flow characteristics in the test section are readily modified due to this modular construction by insertion of flow manipulators either inside the duct or between two sections. This design also makes it extremely easy to modify the wind tunnel test section for investigation of any type of ducted flow, such as that through a 90° corner. The open circuit design also facilitates complete probing of the flow from the downstream end, with probe positioning being accomplished using the motorized 3-dimensional traversing mechanism available with this tunnel.

Instrumentation

Standard hot-wire instrumentation was used for all of the detailed velocity measurements. Single wire probes were operated in the constant temperature mode, along with linearizers to provide output directly proportional to the velocity in the test section. When the situation required, x-wire probes and analog processing

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circuits were used to resolve the three velocity components. The data in this report are presented in the form of traverses across the test section, which are extremely important for evaluating the flow characteristics in the full scale settling chamber and test section. The traverses were obtained using an x-y plotter, with one axis related to the probe position and the other related to the quantity being measured, either mean velocity or turbulence intensity.

Scaling of 5m TDT Turning Vanes

To adequately represent the flow through the 90° corner including the turning vanes, a sufficient number of turning vanes, preferably greater than 6, were to be installed. Given the 15 cm diameter of the test section, there was approximately 21.6 cm available along the 45° joint in the 90° corner. The largest vane spacing was determined as 3.5 cm for 6 turning vanes, giving a geometric scale of approximately 8 to 1 between the full-scale and model facility.

To determine the upper limit of the scale ratio, the full-scale Reynolds numbers were taken into account. With full-scale Reynolds numbers in the range from 1×10^6 to 1.9×10^6, based on the chord of the turning vanes, it was obvious that this could not be approached in our modeling. However, the main influence of the chord Reynolds number is to make the boundary layers sufficiently turbulent. In a scale model of the turning vanes, a Reynolds number of 1×10^5 was thought to be sufficient to provide adequate turbulence in the boundary layers. Even if the initial experiments indicated that this was not the case, the turning vane boundary layers could be tripped. These Reynolds numbers resulted in a maximum scale of approximately 12 to 1.

Another important restriction existed for the mesh Reynolds number of the honeycombs and other turbulence manipulators. Based on 3.25 mm and 12.5 mm mesh honeycombs for the full-scale tunnel, the mesh Reynolds number varied from 1×10^4 to 4×10^4. For the model, a minimum mesh Reynolds number of 4×10^3 was required to ensure turbulent flow in each cell of the honeycomb, as it certainly

would be for the full-scale tunnel. In order to satisfy this requirement, the honeycomb meshes for the model facility were selected as 6.25 mm and 3.13 mm, with 1.56 mm mesh being acceptable, but its Reynolds number was as low as 2500 at the lower speeds.

As a result of these scaling considerations, a prototype to model ratio in the range from 8:1 to 12:1 was required. To make the final decision on the scale, an estimate of the mesh range of possible full-scale tunnel honeycombs was made. Honeycombs in the range from 6.25 mm to 62.5 mm would certainly be considered for modifying the full-scale wind tunnel, with the larger meshes being positioned closer to the turning vanes. Using the 1.56, 3.13 and 6.25 mm mesh honeycombs in the model facility, it was decided to use a 12:1 ratio for the prototype to model ratio; i.e., 1.0 m in the full-scale wind tunnel corresponding to 8.33 cm in the model facility.

Construction of 90° Corner Scale Model

Using a 12:1 scale ratio, it was possible to place 8 turning vanes in the 90° corner, given the 30 cm spacing of the turning vanes in the full-scale wind tunnel. The 90° corner was constructed from the same plexiglas tube used for the test section. The turning vanes are 1/12 scale models of the prototype full-scale turning vanes, based on the original engineering drawings. The turning vanes are made of mahogany and conform quite well to the prototype. These turning vanes mounted in the 90° corner are shown in Figure 2. This section is assembled into the wind tunnel test section for the purpose of performing the experiments. To make the experiments sufficiently general, several flow conditions upstream of the turning vanes were used.

Test Flow Conditions

The flow through the test section in its usual configuration has a turbulence intensity less than 0.5%, especially at higher speeds due to the more efficient blower operation. It was realized that the conditions in the prototype wind tunnel would most likely

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not be as good as this, being of somewhat higher turbulence and possibly contaminated by upstream swirl. To simulate these conditions, a coarse grid upstream of the turning vanes was used to generate turbulence of about 3-4% intensity at the turning vanes. This flow condition is referred to as the "high upstream turbulence" flow condition in the rest of the report. The upstream swirl was generated using the airfoil swirl generator. This generator utilizes two adjacent airfoils, each spanning half of the test section, and set at adjustable equal but opposite angles of attack. A grid was also used in this flow condition to provide additional background turbulence. This flow condition is referred to as the "upstream swirl" flow condition. The third flow condition is the "low upstream turbulence" flow condition utilizing the flow as it usually exists in the test section without modification by flow manipulators.

Manipulator Selection and Construction

As mentioned above, honeycomb meshes of 6.25, 3.13 and 1.56 mm mesh were planned for the experiments. Generally, the length to diameter ratio of the honeycomb is about 10 for efficient operation, resulting in lengths of 62.5 mm and 31.3 mm for the 6.25 and 3.13 mm mesh honeycombs, respectively. To provide adequate strength for the 1.56 mm mesh honeycomb, a length of 25.4 mm was used. All of these mesh sizes were examined in the "new concept" 45° configuration, but only the 3.13 mm mesh was incorporated in the conventional manner.

As discussed in much of the earlier work[2,3], a screen in combination with the honeycomb can lead to much improved turbulence reduction. For this purpose, a 0.91 mm mesh screen was positioned downstream of the honeycomb in the conventional honeycomb case, as well as in the "new concept" 45° honeycomb cases. For this purpose, a fixture was constructed which fits inside the plexiglas test section duct and holds a screen at 45° to the mean flow downstream of the honeycomb and turning vanes. This is in contrast to the usual method of mounting such flow manipulators between sections of the test section in this tunnel.

However, there still remained the problem of constructing the special "new concept" 45° honeycomb. After much discussion, two methods were eventually used. The first involved having the manufacturer cut a 45° angle on the honeycomb before it is expanded to its final form. There is enough rigidity in the compressed honeycomb for this to be done cleanly. However after the honeycomb is expanded, the edges of the honeycomb are not straight, but are somewhat of a saw-tooth shape. While this is not that objectionable, the process is expensive.

The other alternative is to take a straight honeycomb and to saw it at 45° to the cell axes. There are several disadvantages to this method. First, there is a great deal of waste in the sections of the honeycomb not used, especially if any appreciable spanwise distance is to be covered. It also requires a honeycomb of fairly large length/cell diameter ratio. Another disadvantage is that the cell walls are not very rigid, and that the sawing operation leaves a rough edge (even folded over in some cases). No satisfactory method was established to saw the honeycomb cleanly in its expanded state. Careful hand sanding of the rough edges did provide a clean finish, but the process was very time consuming.

EXPERIMENTAL RESULTS

The experiments were conducted according to the schematic shown in Figure 1. The open circuit design of the wind tunnel allowed easy access to the flow downstream of the turning vanes or any flow manipulators inserted in the duct. The three different upstream flow conditions (low turbulence, high turbulence and swirl) were generated as described in the previous section on the test facility and instrumentation. With the 90° corner and the turning vanes mounted as part of the test section of the wind tunnel, the first step was to document the flow downstream of the turning vanes. For almost all of the experimental data, velocity profiles downstream of the turning vanes were taken along lines perpendicular to the mean flow, i.e., the 'y' direction as shown in Figure 1. For wind tunnel applications, this direction is most appropriate, since the spatial uniformity in this direction of important flow characteristics, such as the turbulence intensity, will help assure a similar uniformity in the test section. A few profiles were also taken in the 'z' direction, perpendicular to the 'x' and 'y' directions, and the flow characteristics were quite uniform, as expected.

Flow Downstream of the Turning Vanes

The 90° corner and turning vanes were mounted in the wind tunnel as shown in Figures 1 and 2, with a low turbulence flow entering the turning vanes. Traverses in the 'y' direction were taken at several downstream positions, and the results are plotted in Figure 3, where the downstream distance 'x' is defined with the origin at the inside corner of the 90° turn which contains the turning vanes, as indicated on Figure 1. Please note the greatly expanded scale for the velocity axis of the profiles, which will be used in every case to accentuate whatever nonuniformities that may exist. The reader should also be cautioned about the behavior outside the central region of the duct, i.e., between dashed lines on figures. These regions are only useful for predicting the conditions near the walls of the full-scale settling chamber. From the profiles of the mean velocity $\bar{U}$, the wake of each turning

vane is clearly evident, especially for the traverse taken at
x = 3.13 cm.   The wakes become stronger as the value of y decreases
since the vanes are closer to the probe at the inside corner. This
is a result of the turning vanes being at 45° to the axis of the
downstream duct, i.e., the 'x' direction, while the 'y' direction
is at 90° to this axis, as shown in Figure 1. As one would expect,
the wake defects become less noticeable as they merge, eventually
resulting in a flow which is reasonably uniform at x = 21.6 cm.
The turbulence intensity u'/U_{∞} also decreases and becomes more
uniform as the distance from the turning vanes increases and the
turbulence decays. For the definition of turbulence intensity,
u'/U_{∞}, u' is the rms of the U component velocity fluctuations,
while U_{∞} is the spatial average of the mean velocity $\overline{U}$. The
turbulence intensity is higher for negative values of y, again since
there is less distance from the turning vanes to the probe location.
These results indicate that the turning vanes operate as intended
and that the flow characteristics downstream of these model
turning vanes represent the expected full-scale situation. The
accuracy of this representation depends on a comparison with full-
scale data, which unfortunately were not available. The rate at
which the wakes merge and the mechanism behind the process is
extremel, important for optimum placement of any flow manipulators
and will be discussed later in this section.

To further document the flow conditions which were used for
the experiments, the transverse distributions of mean velocity
$\overline{U}$ and turbulence intensity u'/U_{∞} are plotted in Figures 4 and 5,
respectively, for conditions of low upstream turbulence, high
upstream turbulence, and upstream swirl. All of the results are
for data taken at a probe location of x = 21.6 cm, as this
position approximates the average location of the start of the
contraction for many wind tunnels (although many have shorter
settling chambers and some are longer). Knowledge of the turbulence
intensities at this location also approximates what would be
entering the contraction after a rather short but not unreasonable
decay distance from the last flow manipulator.

Upon examining the data presented in Figures 4 and 5, it

became apparent that the higher upstream turbulence results in spatially more uniform mean velocity and turbulence intensity distributions with essentially no change in the turbulence level from the low upstream turbulence case. The presence of upstream swirl does not affect the mean velocity profile very much, (i.e., the downstream flow is quite similar to the low turbulence case) although the turbulence intensity is less uniform. Detailed measurements of the three velocity components proved that there was essentially no swirl emerging from the turning vanes, even though it was quite strong upstream of them. Based on these results, only the high and low upstream turbulence conditions were used for further experiments. These results also indicate that the turbulence in the settling chamber is dominated by that generated by the turning vanes. However, the role of upstream turbulence is important in the initial decay of the wakes from these vanes.

As the 45^C honeycomb concept is quite new, a means of evaluating its effect on the turbulence as compared with more conventional methods was desired. For this reason, a standard "conventional" honeycomb and low-solidity screen combination was used for both low and high upstream turbulence to develop the typical expected turbulence level. These results are also shown on Figures 4 and 5 for the mean velocity and turbulence intensity, respectively. It is apparent that the spatial uniformity of both the mean velocity and turbulence intensity is slightly improved for higher upstream turbulence. Approximately the same overall turbulence level is achieved by this manipulator for both high and low upstream turbulence conditions. Obviously, the results in both cases are improved over having the turning vanes alone. While this honeycomb-screen combination is an efficient turbulence management solution, the actual solutions are usually more complicated, involving several flow manipulators. Even so, the data show that conditions in the test section are quite good, both in magnitude and uniformity, as well as being reasonably independent of upstream turbulence conditions, which is always desirable. Again, the important comparisons between figures are made here in the central part of the

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duct inside the two dashed lines.*

This completes the description of the basic flow conditions
and the standard (or typical) turbulence improvement which is
used as the basis for comparison with the results of the "new
concept" honeycomb and screen combination, as well as other flow
manipulators. The flow characteristics downstream of each flow
manipulator (and combinations) are discussed in detail in the
following for the two test flow conditions.

Effect of a 45° Screen

It has been previously documented[2,3] that the addition of a
screen at the downstream end of a honeycomb substantially improves
the effectiveness of the honeycomb in reducing the turbulence.
Anticipating that a similar effect is present using a 45° screen
in combination with the 45° honeycomb, a 45° screen was made to
be used either by itself or in a combination at the downstream
end of the 45° honeycomb, as discussed in the chapter on test
facilities and instrumentation.

The use of a screen positioned along the downstream edges of
the turning vanes has also been proposed as one means of modifying
the turbulence as soon as it enters the settling chamber. It is
also advantageous from an installation viewpoint, in that it
would be much simpler to mount the screen along the downstream
edges of the turning vanes than to stretch the screen across the
entire settling chamber, especially in large wind tunnels.
Both of these concepts were examined in this investigation.

Using a section of the screen material selected for this
experiment (an 0.91 mm mesh screen with a solidity of 0.35),
measurements were taken downstream of the screen when it was
positioned at the downstream edge of the turning vanes. The
profiles of mean velocity and turbulence intensity at several
downstream positions are plotted in Figure 6. Examining the mean
velocity profiles, the wake defect from some of the turning vanes

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*The dashed lines on each figure correspond to those shown on
 Figure 1, indicating the region of the duct which is influenced
 by the sidewall boundary layers. Between the dashed lines, the
 flow represents conditions that exist in the full-scale wind tunnel.

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is visible close to the turning vanes, but the wakes merge quickly
with increasing downstream distance. At every downstream location,
the wake defects are much less evident than they are with the
turning vanes alone. However, there is another characteristic
of these profiles which is very detrimental. Note that, at every
downstream location, there is a persistent gradient in the mean
velocity in the 'y' direction with the mean velocity approximately
15% higher downstream of the outside of the corner. This is caused
by the turning effect of the screen, a well-documented phenomenon
which has been used advantageously in other experiments[7] to generate
mean velocity profiles with a desired shape. It is based on the
observation that if the flow into the screen is at an angle other
than 90°, the flow tends to leave at an angle closer to 90°. In
this case, the turning due to the screen counteracts the effects
of the turning vanes, resulting in a non-zero velocity component
towards the outside of the corner. The shear flow generated
persists for all downstream distances, and if this scheme is used
in a full-scale facility, it would certainly be present in the
test section. As a result, the 45° screen alone, either immediately
or some distance downstream of the turning vanes, is not suitable
as a turbulence manipulator due to these effects on the mean flow.
It does however, reduce the turbulence level somewhat from that
existing in the tunnel without the screen. The extent of this
effect will be discussed in more detail later in this chapter.
As stated above, the main purpose of the screen is to use it in
combination with the honeycomb, and these results are presented
in the next section.

45° Honeycomb and 45° Screen

Several honeycombs were constructed based on the "new concept,"
where the honeycomb can be mounted up against the turning vanes,
at 45° to the mean flow, yet with the cells aligned with the flow
direction. Three mesh sizes were used, 1.56, 3.13 and 6.25
mm, with the honeycombs having a length/cell diameter ratio
of 16, 10 and 10, respectively. Further construction details
are found in the section on the flow manipulators.

Selecting the 3.13 mm mesh 45° honeycomb, which is optimally scaled with the screen, the effectiveness of the honeycomb and honeycomb-screen combination was documented with the honeycomb positioned at the downstream end of the turning vanes, i.e., $\Delta x = 0$ in Figure 1. There are several important characteristics of the flow apparent from the mean velocity and turbulence intensity profiles presented in Figure 7. Considering the mean velocity first, the wake from each turning vane is clearly visible at the probe position $x = 21.6$ cm, both with and without the screen. These wake defects are noticeably smaller when the screen is present at the downstream end of the honeycomb. An encouraging observation is that there is hardly any evidence of the mean shear noticed in Figure 6. Both of these results suggest that the 45° screen can be effectively used with the 45° honeycomb. The turbulence intensity profiles indicate that the screen contributes to reducing and uniformizing the turbulence level although there is still a large amount of spatial variation. Based on these observations, all subsequent results in this chapter will be presented for the 45° honeycomb in combination with a 45° screen positioned next to the downstream end of the honeycomb.

A disturbing character of these data is the apparent persistence of the wake defects in the mean velocity and the large spatial variations in the turbulence intensity, especially in comparison to Figure 3. The peaks correspond to the shear layers of the turning vanes, and are obvious even at the probe location $x = 21.6$ cm. To determine the extent of this persistence, the results at $x = 21.6$ cm are compared to those at $x = 40.6$ cm in Figure 8. Even at large distances from the turning vanes, $x = 40.6$ cm, each wake defect is clearly visible in the mean velocity profile, although all of them are not quite as large as at $x = 21.6$ cm. The turbulence intensity profile is still quite nonuniform even at this large distance, due to the presence of the shear regions in the mean flow. The increase in rms near the walls is due to the growth of the boundary layer on the wall of the duct. Obviously the nonuniformity caused by the turning vanes lasts for large distances when the 45° honeycomb and screen

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combination is positioned at the downstream end of the turning vanes. Recall from Figure 3 that the wake defects decay rapidly with downstream distance when there is no flow manipulator in the duct. Even with the conventional honeycomb-screen combination in the duct, there was no evidence of the turning vane wakes; see Figures 4 and 5. The wake mixing mechanism present in those cases has been inhibited or eliminated by the presence of the 45° honeycomb. It was also determined in the discussion of Figures 4 and 5 that higher upstream turbulence led to better spatial uniformity of the flow characteristics downstream of the turning vanes. It is hypothesized that the turbulence that was available for mixing the wakes of the turning vanes, both in the mean flow and in the vane shear layers, has been removed by the 45° honeycomb before it was able to have an effect. The turbulence subsequently generated by the 45° honeycomb-45° screen combination is at the wrong scale, probably too small, to have any significant effect on these large scale mean velocity nonuniformities. To establish whether or not this was true, and to determine if there was an effective way to correct the problem, the following experiments were conducted.

Effect of Separation Between Turning Vanes and 45° Honeycomb

If the honeycomb removed turbulence from the flow which was of a scale suitable for the wake mixing, some separation between the turning vanes and the upstream end of the honeycomb, Δx, should give the existing turbulence a chance to mix the wakes before the honeycomb removes it and generates its own turbulence of a different scale. Figure 9 shows the mean velocity and turbulence intensity profiles for three separations, Δx equals 0, 2.5, and 5.0 cm. Recall that the spacing between the turning vanes is about 2.5 cm as well.

The effect of providing some decay time for the wakes to merge before they enter the 45° honeycomb-45° screen combination is quite clear, with the spatial uniformity in mean velocity improving as the separation increases. At a separation $\Delta x = 5.0$ cm, the uniformity is about as good as that downstream of the conventional

honeycomb and screen as shown in Figure 4. A similar improvement
is noted in the turbulence intensity profiles, particularly between
the cases $\Delta x = 0$ and $\Delta x = 2.5$ cm. However, with an increase in
Δx, the honeycomb becomes closer to the probe since the probe
position is fixed at $x = 21.6$ cm; see Figure 1. In spite of
the shorter decay distance as Δx increases, the average turbulence
intensity is decreasing.

This result not only substantiates our hypothesis on the
importance of the turbulence generated by the turning vanes in
initially uniformizing the mean velocity and turbulence intensity,
but also indicates one possible solution to the problem of the
persistent wake defect when using the 45° honeycomb-45° screen
combination. The feasibility of using separation depends on the
design of the tunnel, as a Δx of 2 vane spacings is apparently
adequate to provide sufficient uniformity.

Effect of 45° Honeycomb Mesh Size

Another variable of importance is the mesh size of the honey-
comb, as this determines the dominant generated-turbulence scales.
The relationship between the scales for each turbulence generating
device influences the overall performance. On Figures 10 and 11
are shown the mean velocity and turbulence intensity profiles
obtained using the three different honeycomb mesh sizes, 1.56,
3.13 and 6.25 mm, at two separations, $\Delta x = 0$ and $\Delta x = 5.0$ cm.

Concentrating first on the results for $\Delta x = 0$, increasing
the honeycomb mesh size decreases the magnitude of the wake defects
from the turning vanes. This is due to the larger-mesh honeycomb
generating larger scales that are better suited for effectively
mixing the wakes. However, the spatial uniformity of the mean
velocity is still not as good as that which can be obtained using
separation between the honeycomb and the turning vanes, as shown
in Figure 9. The turbulence level is also highest downstream of
the 6.25 mm mesh honeycomb. This is partly because the downstream
end of the longer larger-mesh honeycombs is closer to the probe
position, $x = 21.6$ cm, and partly because the turbulence
reduction is not as effective with the larger honeycomb, due to

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the generated turbulence characteristics. The same 45° screen was also used with all three honeycombs, and previous work has shown that there is an optimum mesh ratio between the screen and honeycomb of 3 or 4 to 1, (see Ref. 2). The screen used for these experiments matches the 1.56 and 3.13 mm mesh honeycombs better. One other detrimental effect of the larger mesh honeycomb is that there is substantially more mean shear generated by the turning action of the screen, as described in detail for Figure 6. Presumably this would not be the case if the screen mesh was appropriately scaled for t´e larger mesh honeycomb to optimize the blockage for each cell while generating turbulence of appropriate scale for overcoming the honeycomb generated turbulence.

Considering the case with separation, $\Delta x = 5.0$ cm, the mean velocity profiles again demonstrate the importance of allowing some distance for the turning-vane wakes to mix. The spatial uniformity in both cases is about as good as that obtained for the conventional honeycomb, although there is slightly more mean shear present for the 3.13 mm mesh honeycomb due to the turning effect of the screen. There is a much more significant difference in the turbulence intensity, being quite low for the 1.56 mm mesh honeycomb, and being much more spatially uniform for both mesh sizes as compared with the results for $\Delta x = 0$. However, the pressure drop associated with the 1.56 mm mesh honeycomb is high, and usually does not lead to the most efficient way of improving the turbulence.

The mesh size is therefore quite important, especially if the honeycomb is to be mounted along the turning-vanes trailing edges. The mesh of the honeycomb must be properly scaled to the turning vanes so that the wakes mix quickly. However, the turbulence reduction effectiveness is usually lessened. With some separation, the honeycomb mesh can be selected based on the free-stream turbulence characteristics, much in the same way as for conventional honeycombs[2], with significant improvement in the efficiency of the turbulence reducing flow manipulators.

Before discussing the relative effects of the methods for
reducing the turbulence, one more parameter was investigated for
the "new-concept" honeycomb. As is the case for using any type
of flow manipulator, a very desirable, almost necessary, character-
istic is that the turbulence reduction should be independent of
free-stream velocity.

Effect of Free-Stream Velocity on 45° Honeycomb Performance

The data with the 3.13 mm mesh 45° honeycomb-45° screen
combination downstream of the turning vanes, Δx = 5.0 cm, for
three different free-stream velocities, 20.4, 27.6 and 36 meters per
second, are plotted on Figure 12. Both the mean velocity and
turbulence intensity profiles are reasonably independent of
free-stream velocity, both in spatial uniformity and in turbulence
intensity magnitude. This demonstrates that the use of the 45°
honeycomb and 45° screen combination with a separation Δx = 5.0 cm
from the turning vanes results in the flow characteristics down-
stream being independent of free-stream velocity, and certainly
strengthens the possibilities of using such a combination for
turbulence control.

Relative Effectiveness of Different Types of Turbulence Manipulators

In order to make a final evaluation of the "new-concept" honey-
comb, a direct comparison with the conventional honeycomb as well
as with other flow manipulators is necessary. The flow
characteristics downstream of the "new-concept" 45° honeycomb-45°
screen combination, the turning vanes when there is no manipulator
present, a 45° screen at the turning vanes trailing edge, and a
conventional honeycomb-screen combination, are presented in
Figures 13-16 for both low and high upstream turbulence.
Concentrating first on the results for low upstream turbulence,
Figures 13 and 14, one notes that the conventional honeycomb and
screen combination provides the best spatial uniformity of the
mean velocity, with the 45° honeycomb-45° screen combination
slightly worse, but not much different from the case with no
manipulator in the duct. The 45° screen alone provides the worst

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performance, which was explained previously with the aid of Figure 6. Reviewing the turbulence intensity profiles of Figure 14, the 45° honeycomb-45° screen results in the lowest overall turbulence intensity, although it is less spatially uniform than the turbulence intensity downstream of the conventional honeycomb and screen combination. There is a greater turbulence intensity at the same downstream location for both the 45° screen and the turning vanes alone, with the 45° screen being lower. However, all of these results are for low upstream turbulence and as was noted before, higher upstream turbulence permits better mixing of the turning-vane wakes for more spatially uniform flow characteristics, and is also a more realistic condition for most wind tunnels.

The effects of higher upstream turbulence are demonstrated for any manipulator by comparing the corresponding profiles in Figures 13 and 15. There is a substantial improvement in the mean velocity spatial uniformity in all cases, with greater improvement for the 45° honeycomb-45° screen combination and the 45° screen alone. As a result, the flow downstream of the 45° honeycomb-45° screen combination is now comparable to that obtained with the conventional honeycomb and screen combination. A similar effect is observed for the turbulence intensity, Figure 16, for these flow-manipulator combinations. Again, there is a greater improvement in the uniformity of the flow downstream of the 45° honeycomb-45° screen combination due to the higher upstream turbulence as compared to the conventional honeycomb screen combination; see Figures 14 and 16. Interestingly, there is no appreciable change in the turbulence intensity at the probe position with the much higher upstream turbulence, indicating that both of the honeycomb flow manipulators are at least properly controlling the turbulence.

In summary, the overall flow characteristics downstream of the 45° honeycomb-45° screen combination are comparable to those present downstream of the conventional honeycomb and screen combination, especially for higher upstream turbulence, when the manipulator combination is positioned and scaled correctly.

A single 45° screen along the downstream edges of the turning vanes provides inferior performance, in some respects even worse than with no manipulator downstream of the turning vanes at all. Therefore, the screen above should not be recommended as a logical choice for improving mean velocity and turbulence level in the settling chamber of any wind tunnel.

Summary

In order to attach some overall quantitative significance to the results of Figures 3-16 and to have some measure of the relative performance of each manipulator, the effect on the turbulence intensity for each of the manipulator combinations and their relative positions is compiled in Table 1. In the table, under the heading u'/U_∞ , the turbulence intensity, the numbers in parentheses are approximate maximum and minimum values of the turbulence intensity across the test section, while the third number is a realistic spatial average. It should be noted that the maximum levels occur near the inside corner and may be artificially high due to the sidewall boundary layer or to some separated region at the inside corner. The quantity F_1^* is defined as the ratio of the turbulence intensity downstream of the turning vanes alone to the turbulence intensity at the same downstream position when a flow manipulator is used. The higher the value of F_1^*, the more effective the flow manipulator is at reducing the turbulence. At large downstream distances, i.e. long decay time, turbulence reductions of approximately $2F_1^*$ may be expected.

While all of the values reflect the observations discussed in connection with the appropriate figures, a quantitative comparison of the most promising manipulator combinations is useful. As in the foregoing discussion, the performance level of the 3.13 mm mesh conventional honeycomb and screen combination is used as the standard. With respect to this standard, the 3.13 mm mesh 45° honeycomb-45° screen combination, $\Delta x =$ 5.0 cm, provides slightly better (5% to 10%) overall turbulence reduction for both low and high upstream turbulence, although

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Table 1. Comparison of Manipulator Performance

MANIPULATOR	U_∞(m/sec)	LOW UPSTREAM TURB. u'/U_∞(%)	$F_1^\star$	HIGH UPSTREAM TURB. u'/U_∞(%)	$F_1^\star$
Turning Vanes Alone	≈30	3.6 (4.74 / 2.44)	1	3.8 (4.98 / 3.0)	1
45° Screen, Δx=0	"	2.43 (2.91 / 1.93)	1.48	2.59 (5. . / 2 . . .)	1.47
3.13 mm Mesh Conventional Honeycomb and Screen	"	1.58 (2.02 / 1.14)	2.28	1.58 (1.86 / 1.26)	2.41
3.13 mm Mesh 45° Honeycomb + 45° Screen, Δx=5.0 cm	"	1.47 (2.28 / 0.82)	2.45	1.39 (2.46 / 1.11)	2.73
3.13 mm Mesh 45° Honeycomb + 45° Screen, Δx=2.5 cm	"			2.02 (2.97 / 1.14)	1.88
3.13 mm Mesh 45° Honeycomb Δx=2.5 cm	"	2.53 (4.01 / 1.3.)	1.42		
3.13 mm Mesh 45° Honeycomb + 45° Screen, Δx=0	"	1.74 (2.83 / 0.64)	2.07	1.71 (2.78 / 1.14)	2.22
3.13 mm Mesh 45° Honeycomb Δx=0	"	2.34 (3.75 / 0.96)	1.54		
1.56 mm Mesh 45° Honeycomb + 45° Screen, Δx=5.0 cm	"			1.09 (1.76 / 0.73)	3.49
1.56 mm Mesh 45° Honeycomb + 45° Screen, Δx=0	"			2.15 (3.41 / 1.20)	1.77
6.25 mm Mesh 45° Honeycomb + 45° Screen, Δx=0	"			2.21 (4.02 / 1.42)	1.72
6.25 mm Mesh 45° Honeycomb Δx=0	"	2.78 (4.36 / 1.67)	1.29		
3.13 mm Mesh 45° Honeycomb + 45° Screen, Δx=5.0 cm	≈20.4			1.77 (2.83 / 1.35)	2.15
3.13 mm Mesh 45° Honeycomb + 45° Screen, Δx=0	≈20.4			2.04 (3.44 / 1.39)	1.86
3.13 mm Mesh 45° Honeycomb + 45° Screen, Δx=5.0 cm	≈36.0			1.40 (2.95 / 1.00)	2.71

1. Screen mesh is 0.91 mm in all cases

2. $F_1^\star = \dfrac{(u'/U_\infty)\text{turning vanes alone}}{(u'/U_\infty)\text{manipulator}}$

3. Values of (u'/U_∞) in parentheses are typical maximum and minimum values in the y-direction

there is a larger difference between the maximum and minimum
turbulence intensity levels. This is a reflection of the some-
what higher spatial nonuniformity as observed in Figures 14 and
16. The other manipulator combinations which do as well as, or
better than, the conventional honeycomb and screen combination
can also be easily selected from this table. However, the values
quoted in the table should always be used in connection with
the appropriate figures and discussion before making any conclusions.

CONCLUSION

Based on the results of this investigation and the discussion of the previous section, the following conclusions on the operation of wind tunnel turning vanes and on using the "new-concept" honeycomb in conjunction with these turning vanes can be stated:

1. Higher turbulence upstream of the turning vanes (even a very small increase in turbulence intensity) yields better spatial uniformity of the mean flow and turbulence intensity downstream of the turning vanes, both with and without flow manipulators.

2. Upstream swirl is almost completely eliminated by the turning vanes, even though the swirl has a strong concentrated vortex. The flow manipulators downstream of the turning vanes do not have to be designed to remove such swirls.

3. A single screen stretched across the trailing edges of the turning vanes leads to conditions that are inferior to those present when using the turning vanes alone. Either a conventional honeycomb and screen combination or the "new-concept" 45° honeycomb-45° screen combination would, therefore, offer much better solutions. The addition of a single screen immediately downstream of the honeycomb significantly improves the performance for all honeycombs, especially where the mean velocity is reasonably uniform upstream of the honeycomb.

4. Proper turbulence management solutions, using either the conventional honeycomb and screen combination or the "new-concept" 45° honeycomb-45° screen combination, result in overall flow characteristics essentially independent of conditions upstream of the turning vanes. However, spatial uniformity is affected by the upstream conditions, (see conclusion 1).

5. The "new-concept" 45° honeycomb-45° screen combination with adequate separation from the turning vanes (approximately 2 vane meshes) results in mean flow

conditions and turbulence intensity levels comparable
to those produced by a conventional honeycomb and
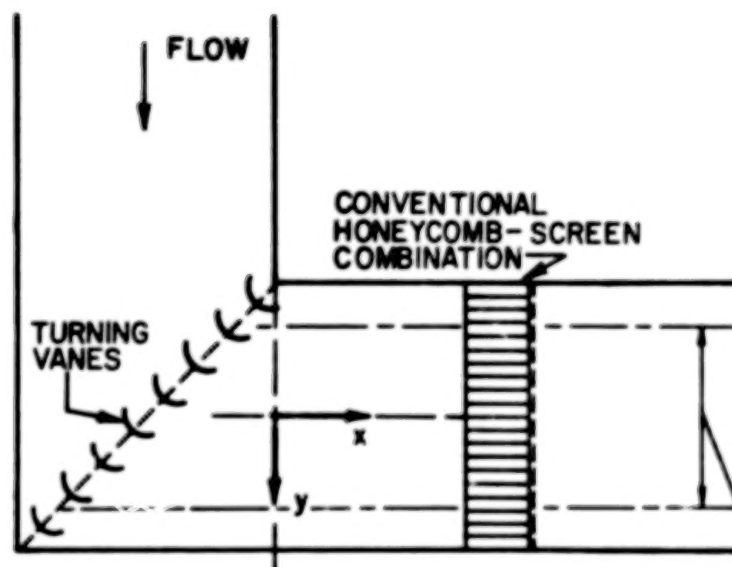screen combination.

6. Separation between the turning vanes and the 45° honey-
comb-45° screen combination leads to improved performance
by allowing the vane wakes some distance to mix and
decay under the influence of their own generated turbulence.
Eliminating the separation distance and placing the
honeycomb too close to the turning vanes removes the
turbulence necessary for efficient wake mixing too soon,
resulting in persistent mean velocity wake defects for
large distances downstream. Adequate separation
distance is approximately 2 vane meshes and is made
shorter by higher upstream turbulence and honeycomb
pressure drop.

7. Using no separation between the turning vanes and the
45° honeycomb-45° screen combination renders the concept
less effective due to the lack of turning vane
wake decay, as described in conclusion 6, resulting
in large spatial nonuniformities and slower turbulence
decay. The honeycomb mesh must be scaled to the turning-
vanes mesh when no separation is used (mesh ratio of
about 5) to improve spatial uniformity, instead of being
scaled to the turbulence characteristics for maximum
turbulence reduction.

8. Proper selection of the honeycomb-screen combination
downstream of the turning vanes could lead to a reduction
in turbulence by a factor of almost 7 ahead of the
contraction and a factor of more than 10 after the
contraction.

As stated above, the "new concept" honeycomb and screen can
be used in place of the conventional honeycomb and screen with
some improvement in the turbulence reduction, if some separation
is provided between the turning vanes and the honeycomb. However,
in the Introduction, it was theorized that by acting on the
turbulence sooner, the turbulence intensity at any position

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downstream should be much lower. The turbulence is also at a later stage of decay, indicating larger scales of the turbulence. Considering the slightly better turbulence reduction using the "new concept" 45° honeycomb-45° screen combination, the real proof of whether or not it is significantly better will depend on the contraction effects on the two turbulent flows of approximately the same turbulence intensity but of different scales. Unfortunately, this question cannot be answered at present, as no study of this effect has been performed to date. Once this information is known, it will then be possible to decide whether the extra expense incurred for fabricating and installing the "new-concept" honeycomb will be justified.

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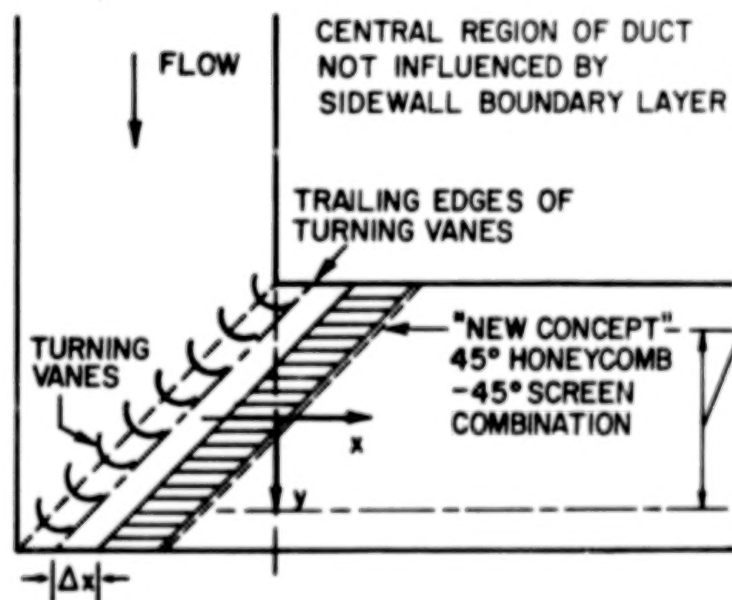
Figure 1. Schematic of proposed "new-concept" 45° honeycomb and comparison with a conventional honeycomb

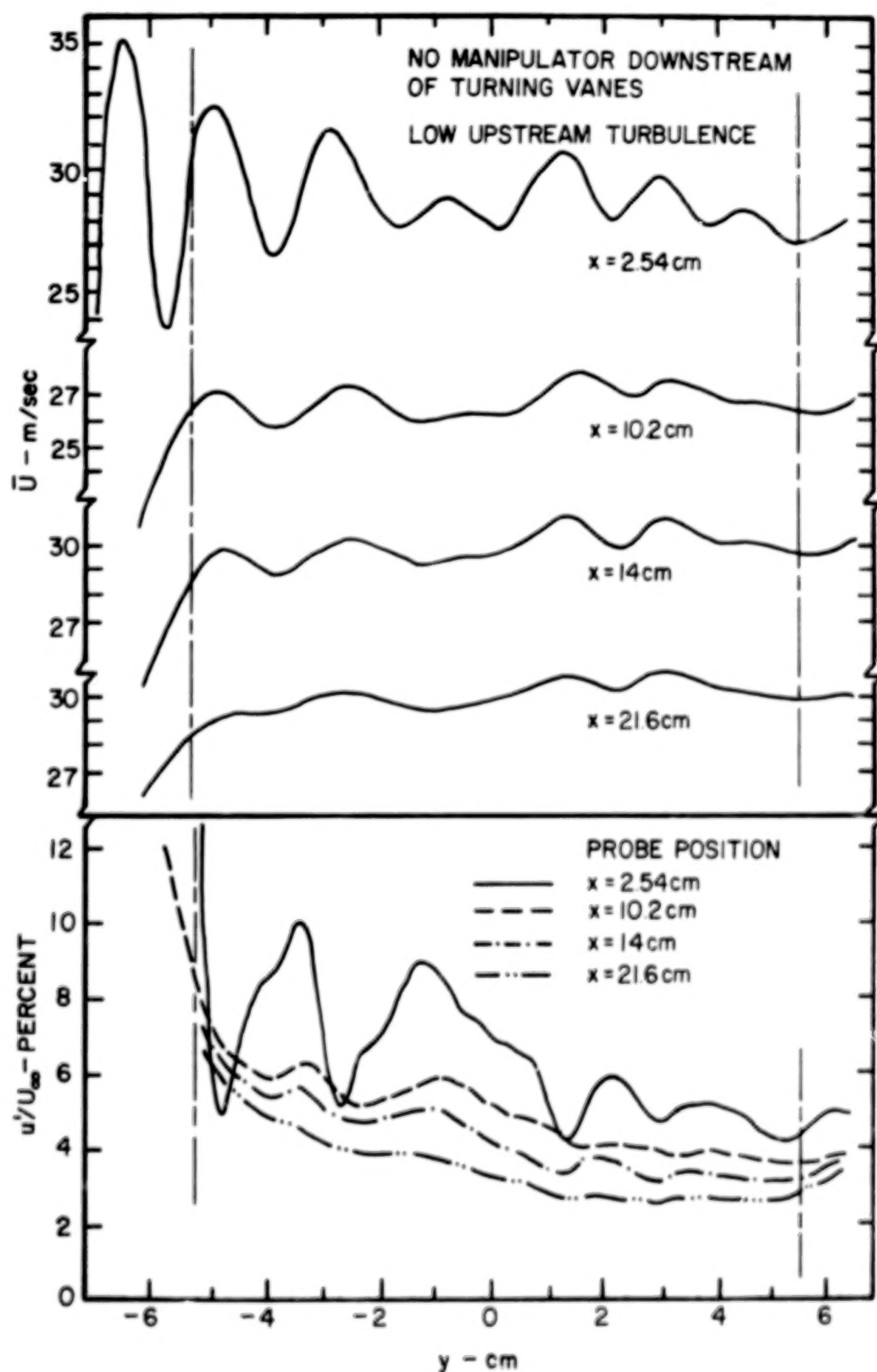Figure 2.   Photograph of scale-model turning vanes mounted in a
   90° corner

28.

Figure 3. Lateral profiles of mean velocity and turbulence intensity at several distances downstream of turning vanes with low upstream turbulence
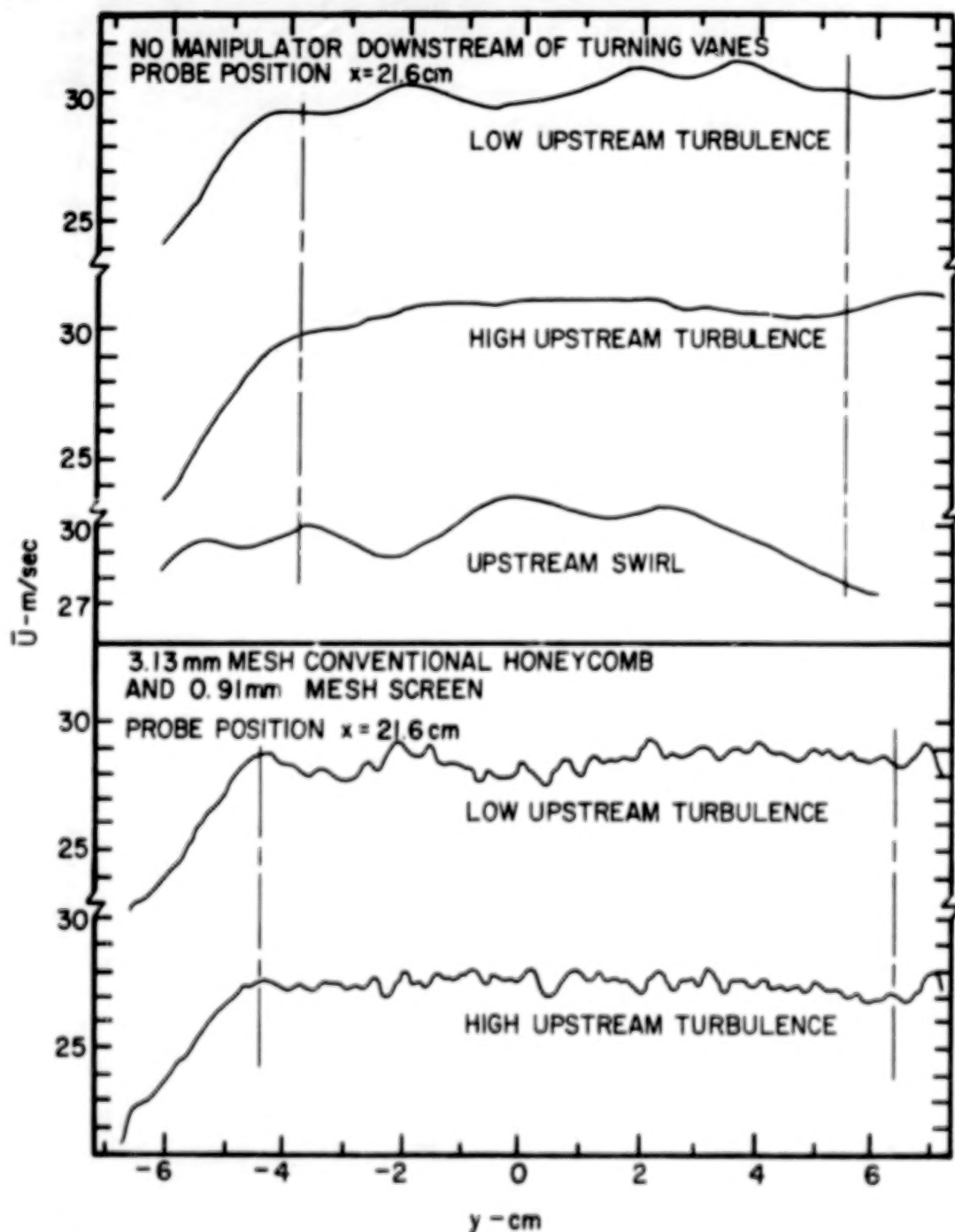
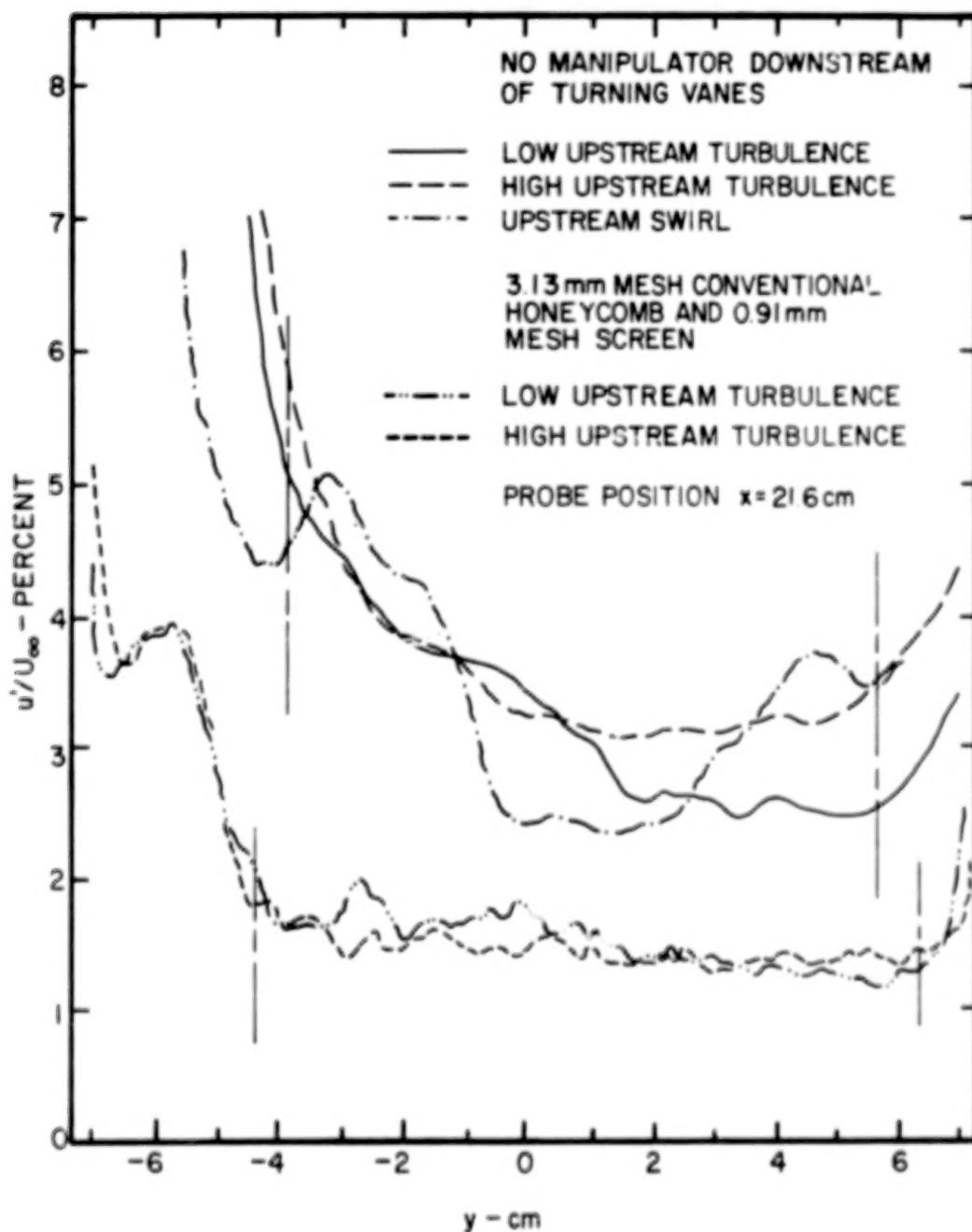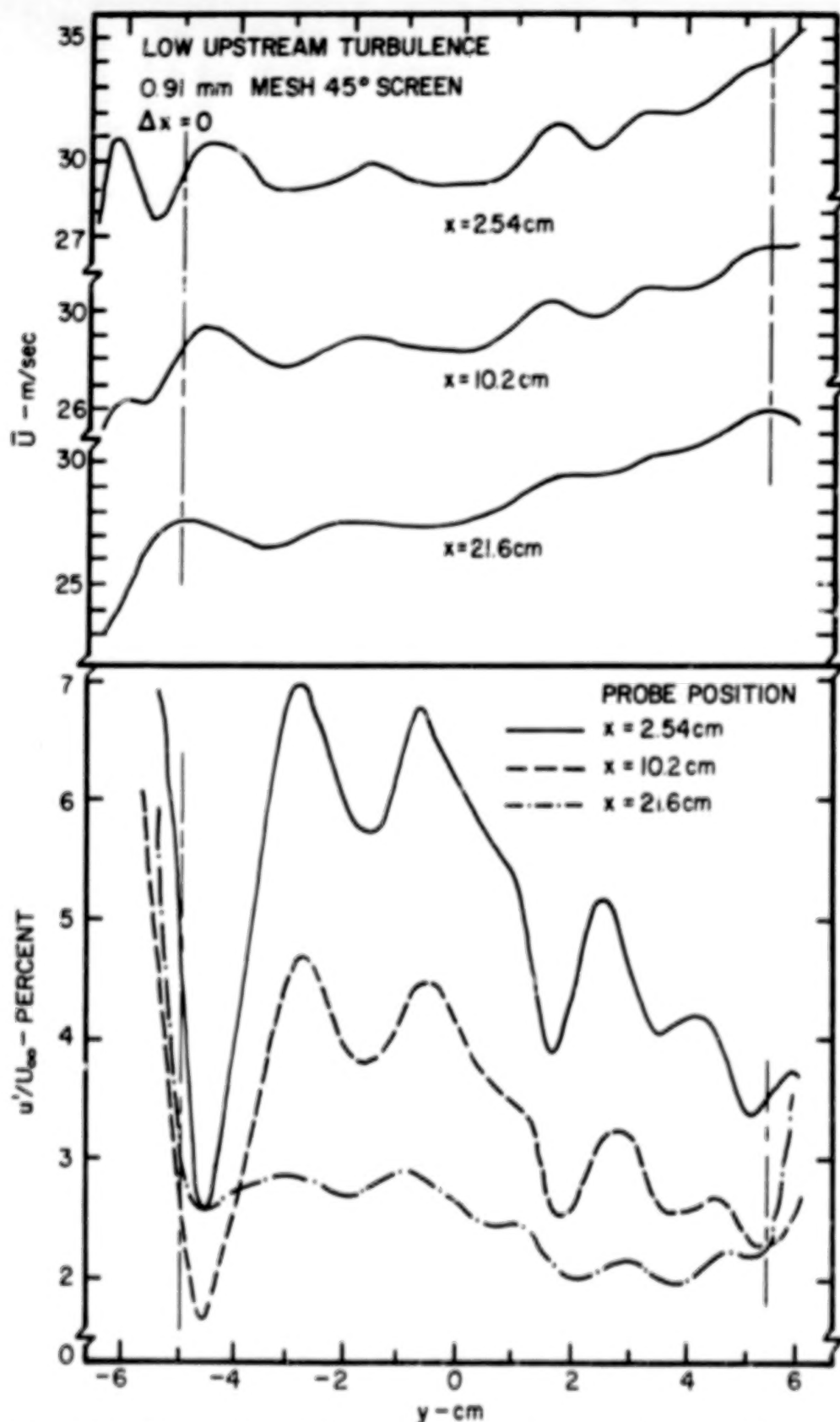Figure 4. Lateral profiles of mean velocity with either a conventional honeycomb or no flow manipulator downstream of turning vanes in several flow conditions

Figure 5. Lateral profiles of turbulence intensity with either a conventional honeycomb or no flow manipulator downstream of turning vanes in several flow conditions
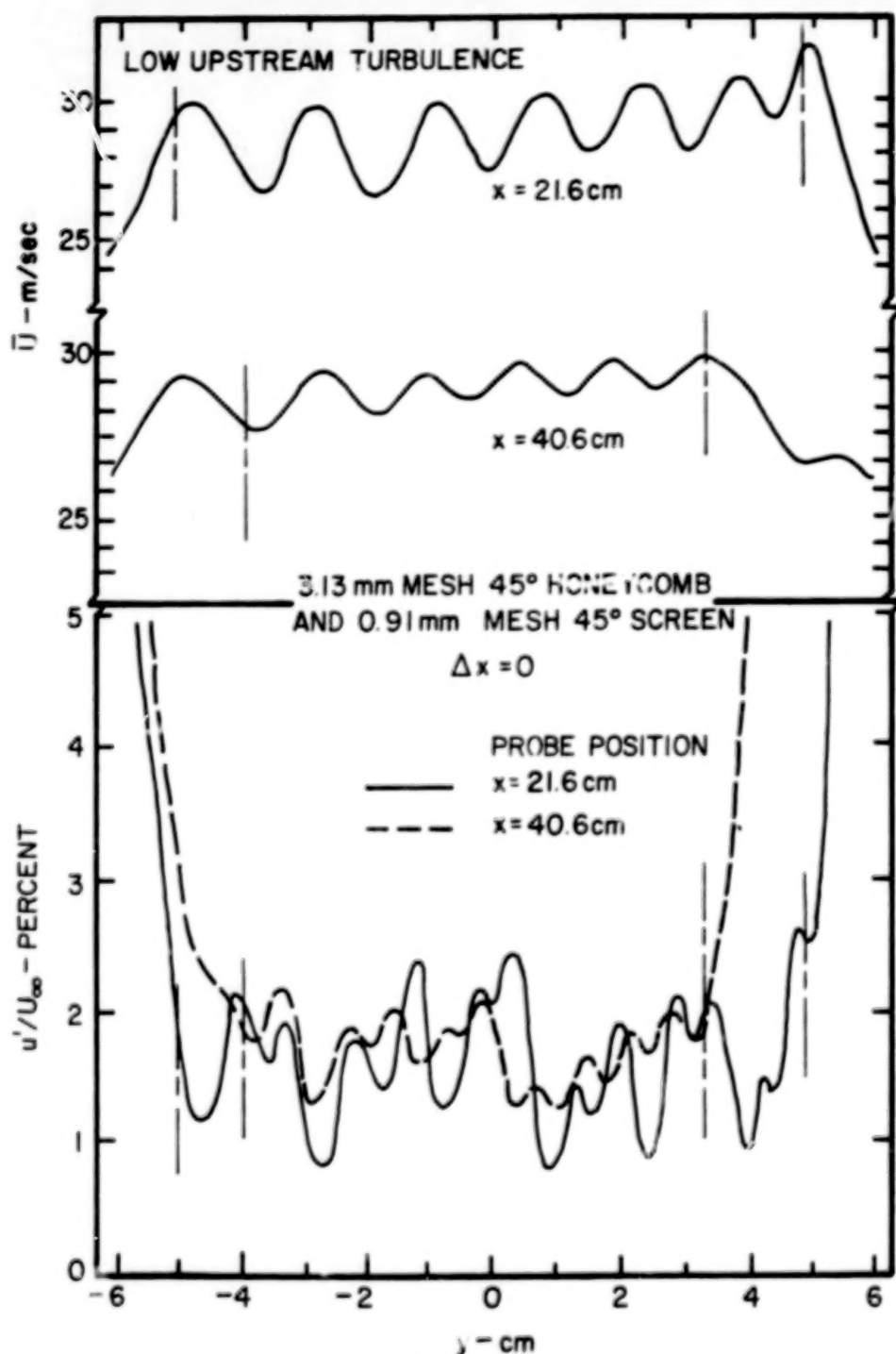
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Figure 6. Lateral profiles of mean velocity and turbulence intensity at several distances downstream of turning vanes with a 0.91 mm mesh 45°-screen positioned at trailing edges of turning vanes in low turbulence flow condition
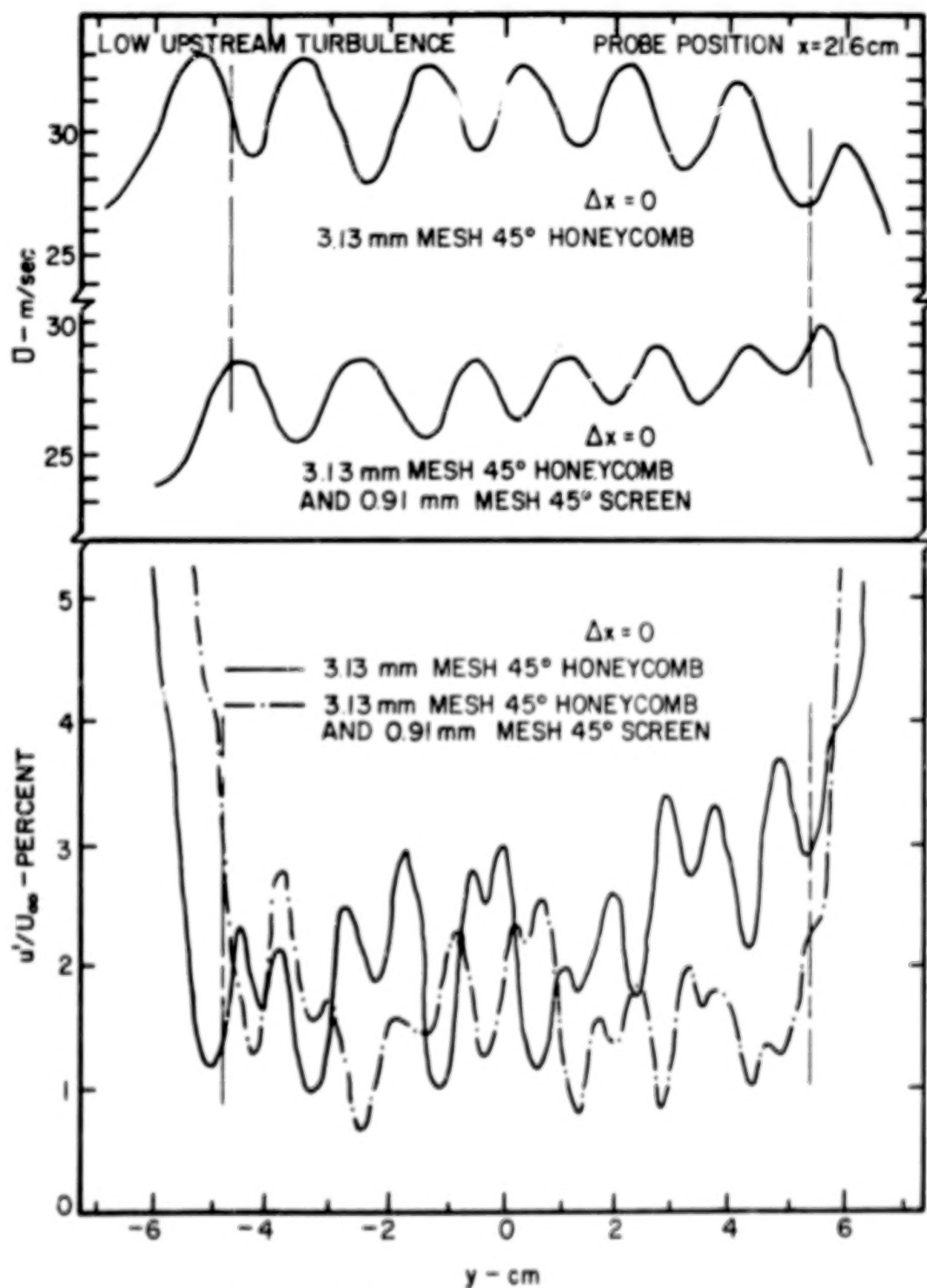
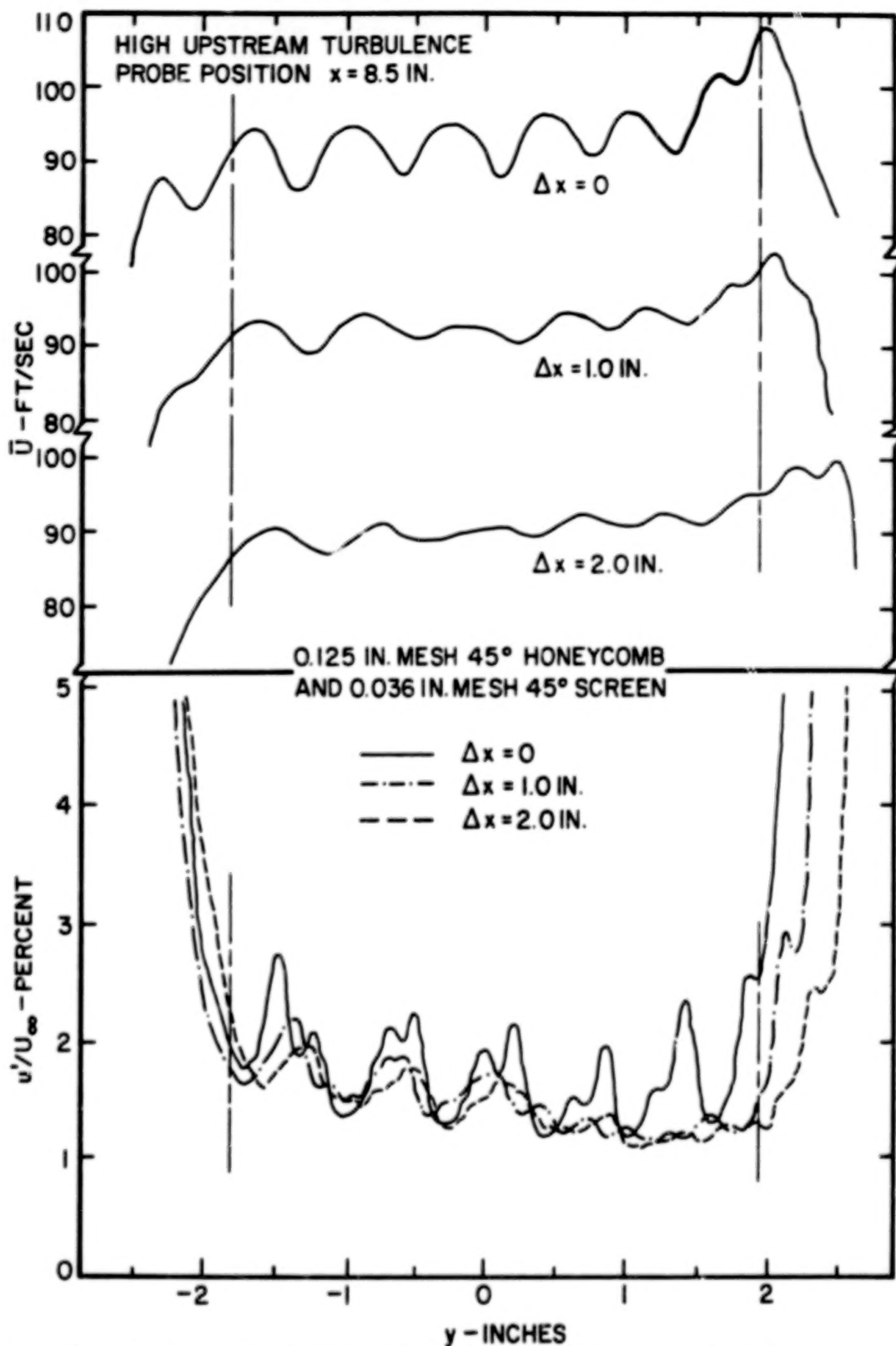Figure 7. Lateral profiles of mean velocity and turbulence
intensity with a 3.13 mm mesh 45°-honeycomb positioned
at trailing edges of turning vanes with and without a 0.91 mm
mesh 45°-screen at downstream end of honeycomb in low
turbulence flow condition

Figure 8. Lateral profiles of mean velocity and turbulence intensity
for two distances downstream of turning vanes with a 45° honeycomb-
45°-screen positioned at trailing edges of turning vanes in low
turbulence flow condition

Figure 9.   Effect of separation between 45° honeycomb-45° screen combination and trailing edges of turning vanes on lateral profiles of mean velocity and turbulence intensity in high turbulence flow condition
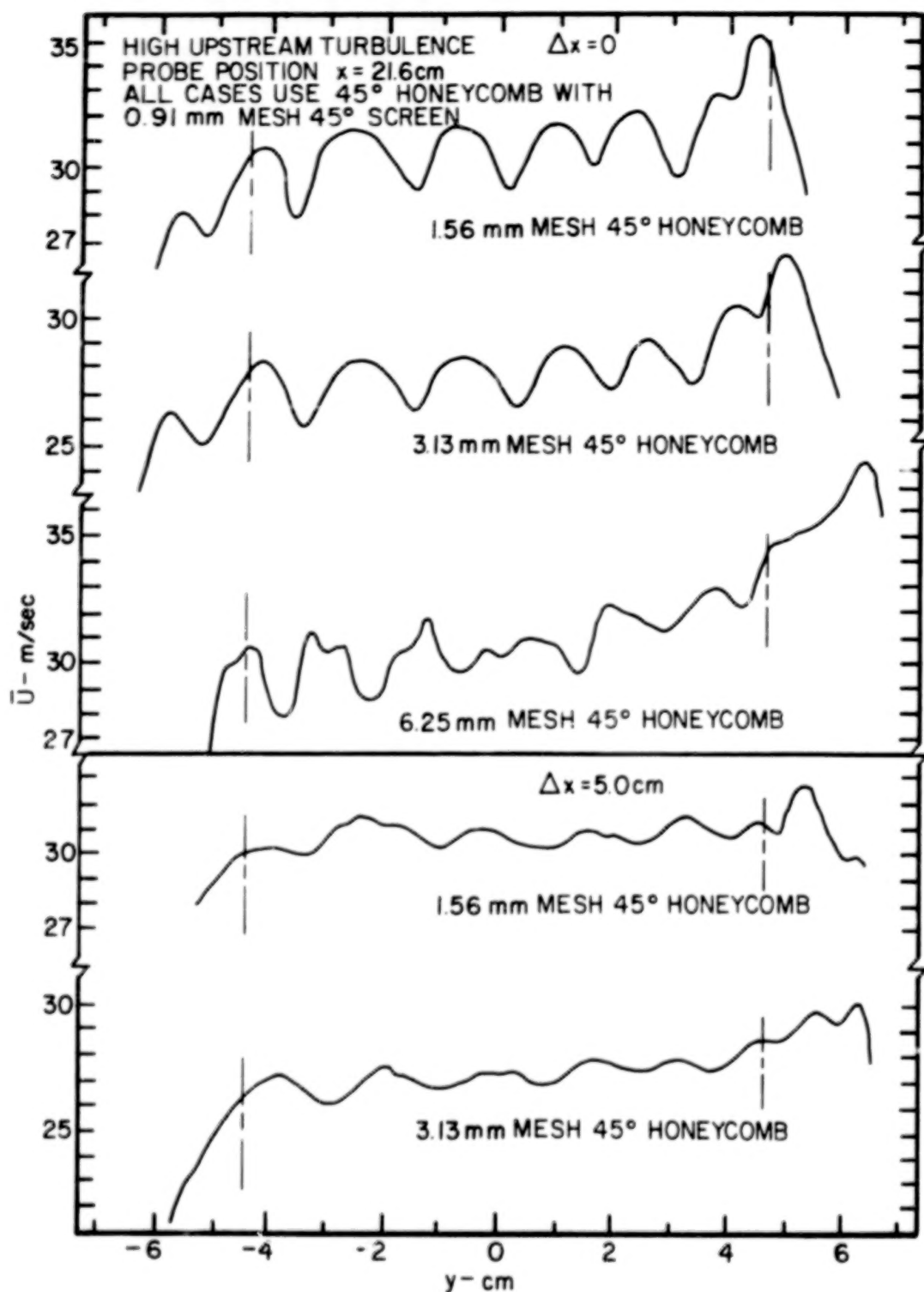
Figure 10. Effect of 45°-honeycomb mesh on lateral profiles of mean velocity for a 45° honeycomb-45° screen combination with no separation from turning vanes, Δx=0, and Δx=5.0 cm in high turbulence flow condition
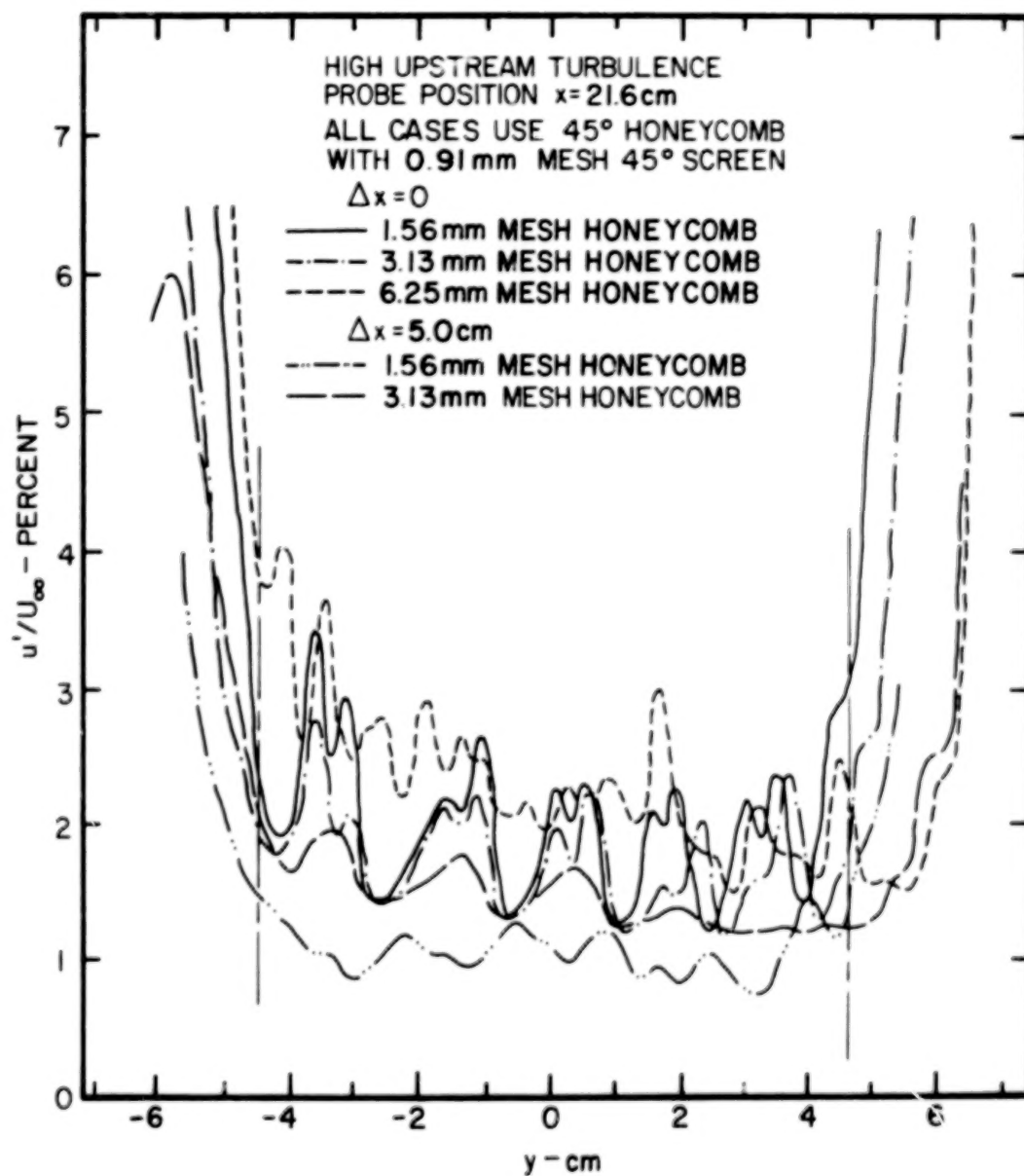
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Figure 11. Effect of 45°-honeycomb mesh on lateral profiles of turbulence intensity for a 45° honeycomb-45° screen combination with no separation from turning vanes, Δx=0, and Δx=5.0 cm in high turbulence test flow condition
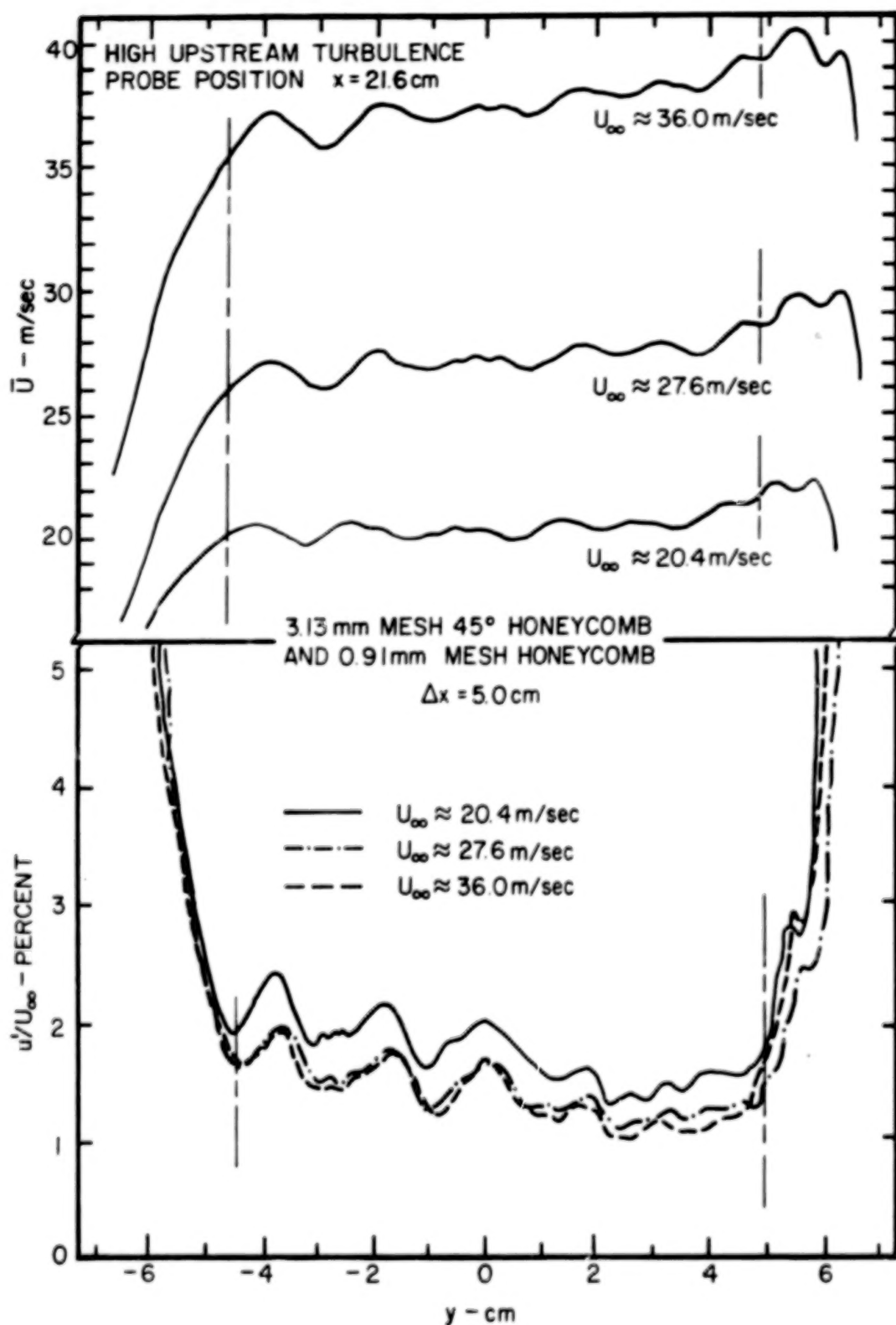
Figure 12. Lateral profiles of mean velocity and turbulence intensity for three free-stream velocities with a 45° honeycomb-45° screen combination downstream of turning vanes and separation Δx=5.0 cm
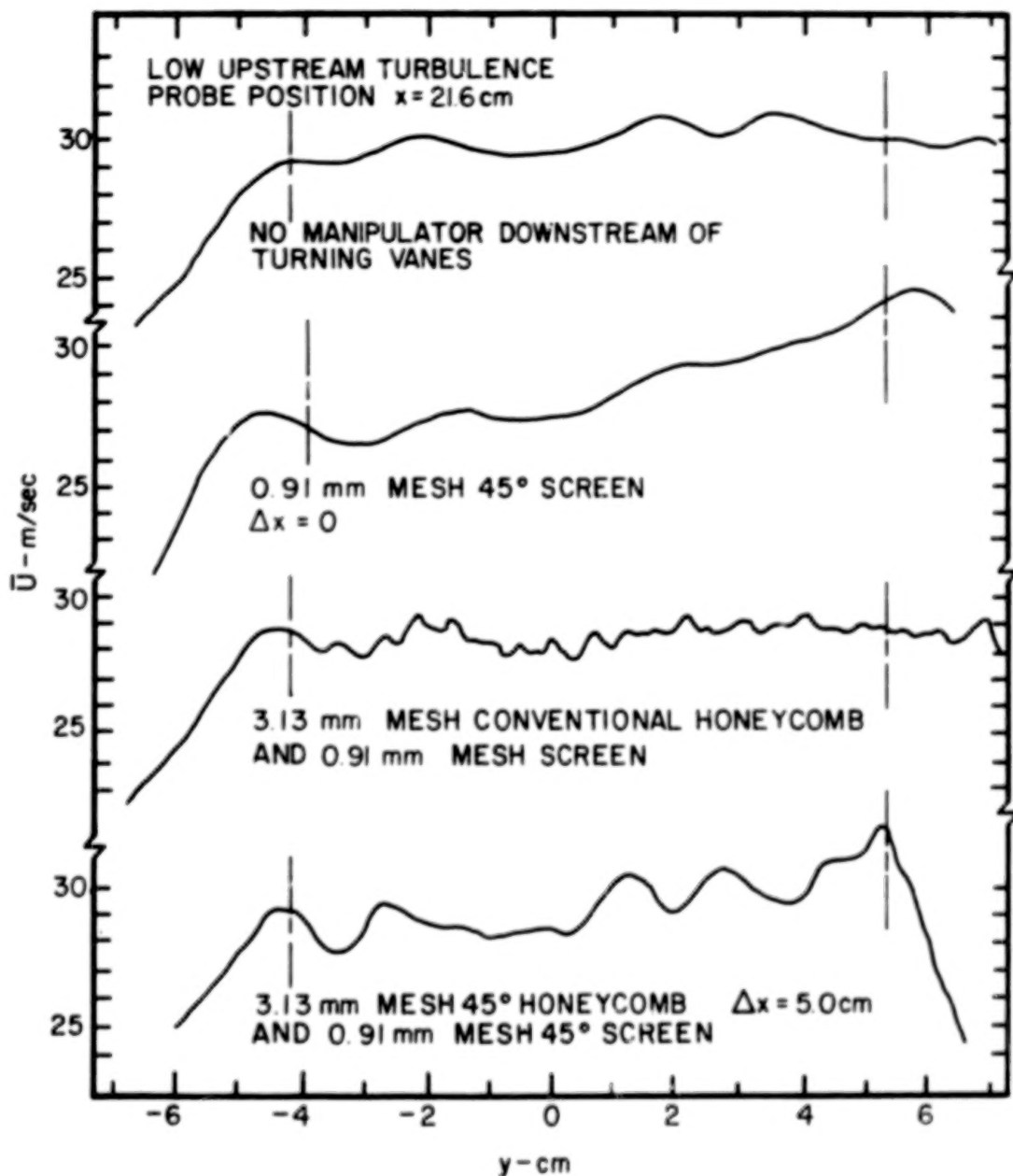
Figure 13. Effect of using no manipulator, a 45°-screen, a conventional honeycomb-screen combination, and a 45° honeycomb-45° screen combination downstream of turning vanes on lateral profile of mean velocity in low turbulence flow condition
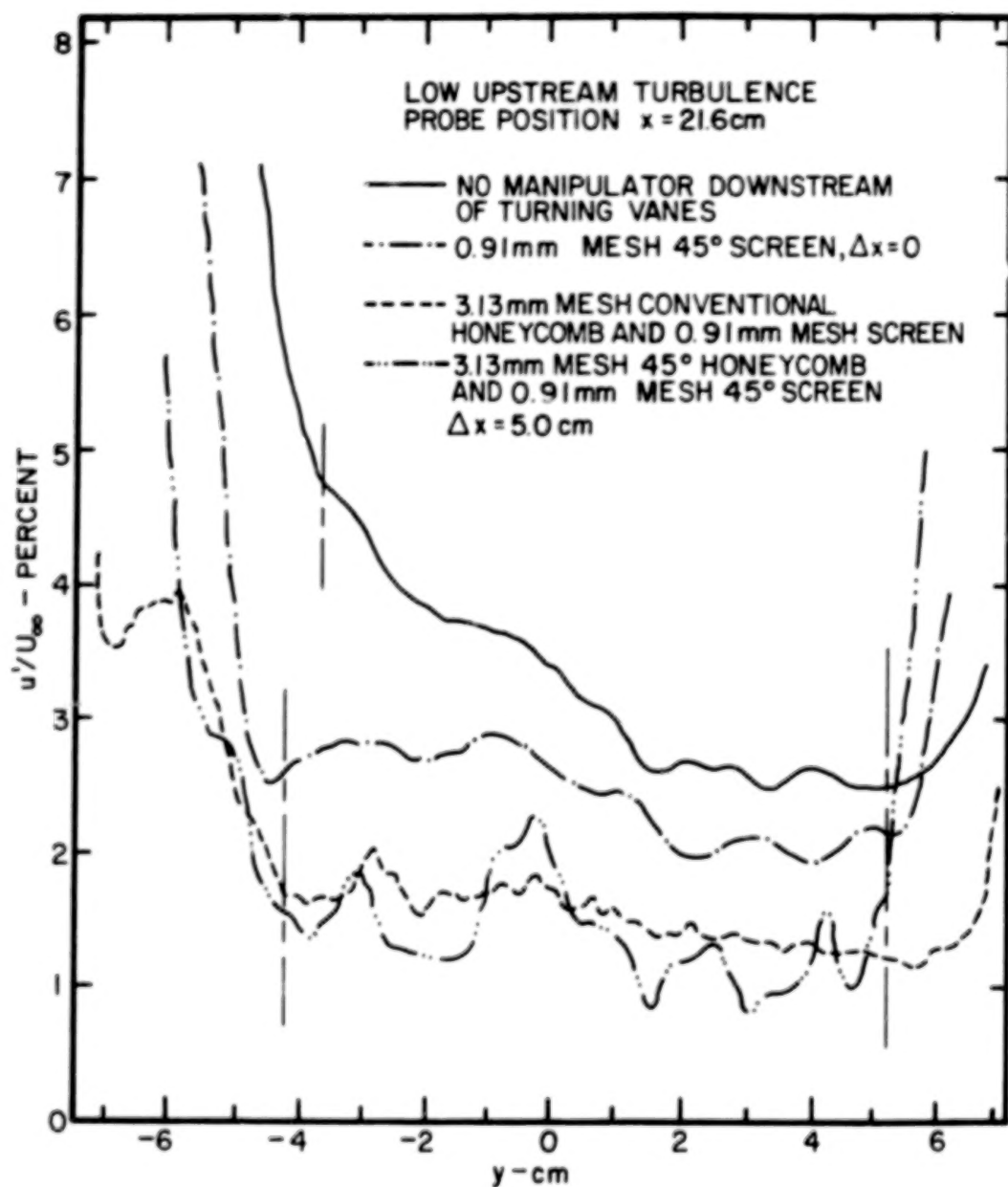
Figure 14. Effect of using no manipulator, a 45°-screen, a conventional honeycomb-screen combination, and a 45° honeycomb-45° screen combination downstream of turning vanes on lateral profile of turbulence intensity in low turbulence flow condition

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Figure 15.   Effect of using no manipulator, a 45°-screen, a conventional honeycomb-screen combination, and a 45° honeycomb-45° screen combination downstream of turning vanes on lateral profile of mean velocity in high turbulence flow condition
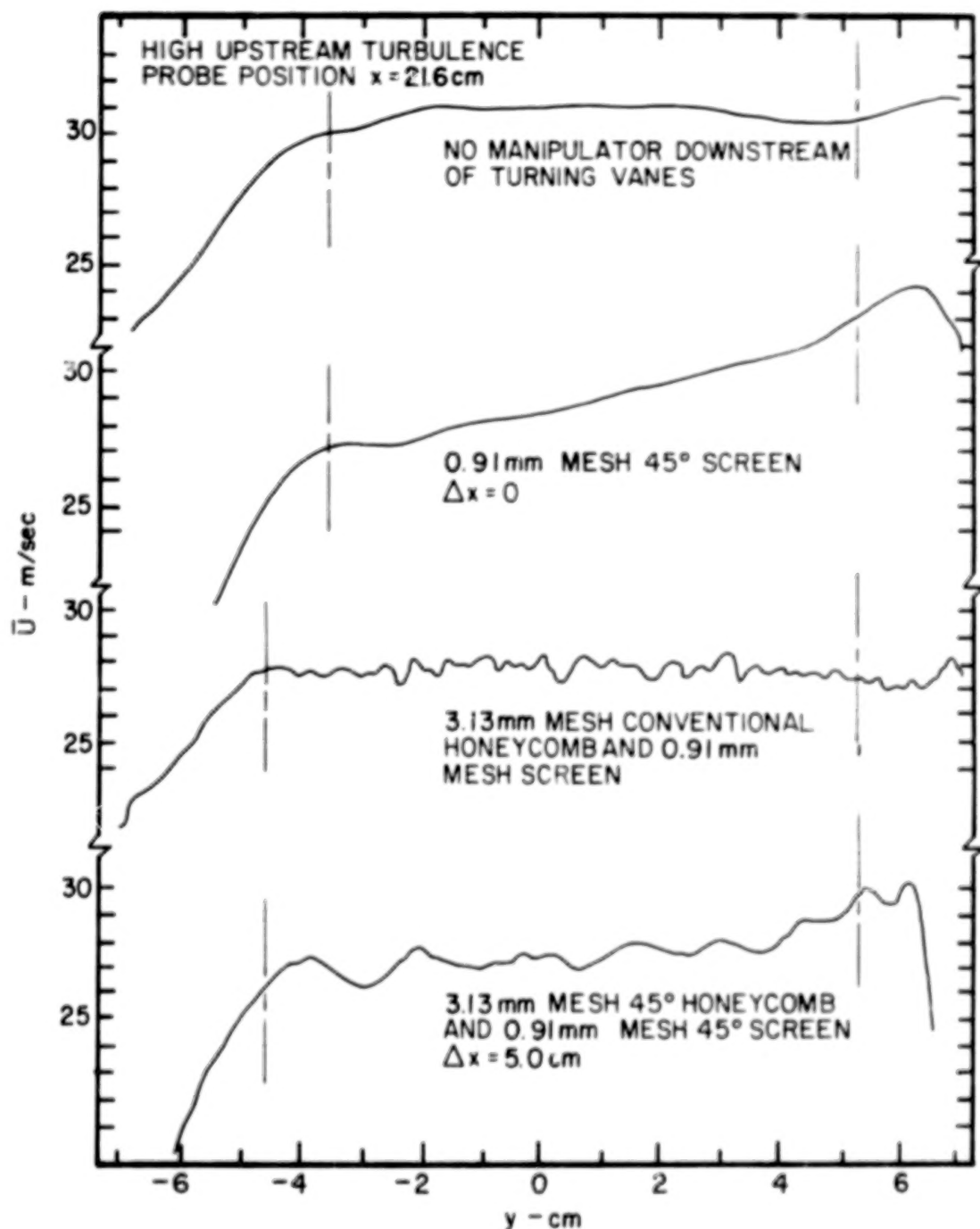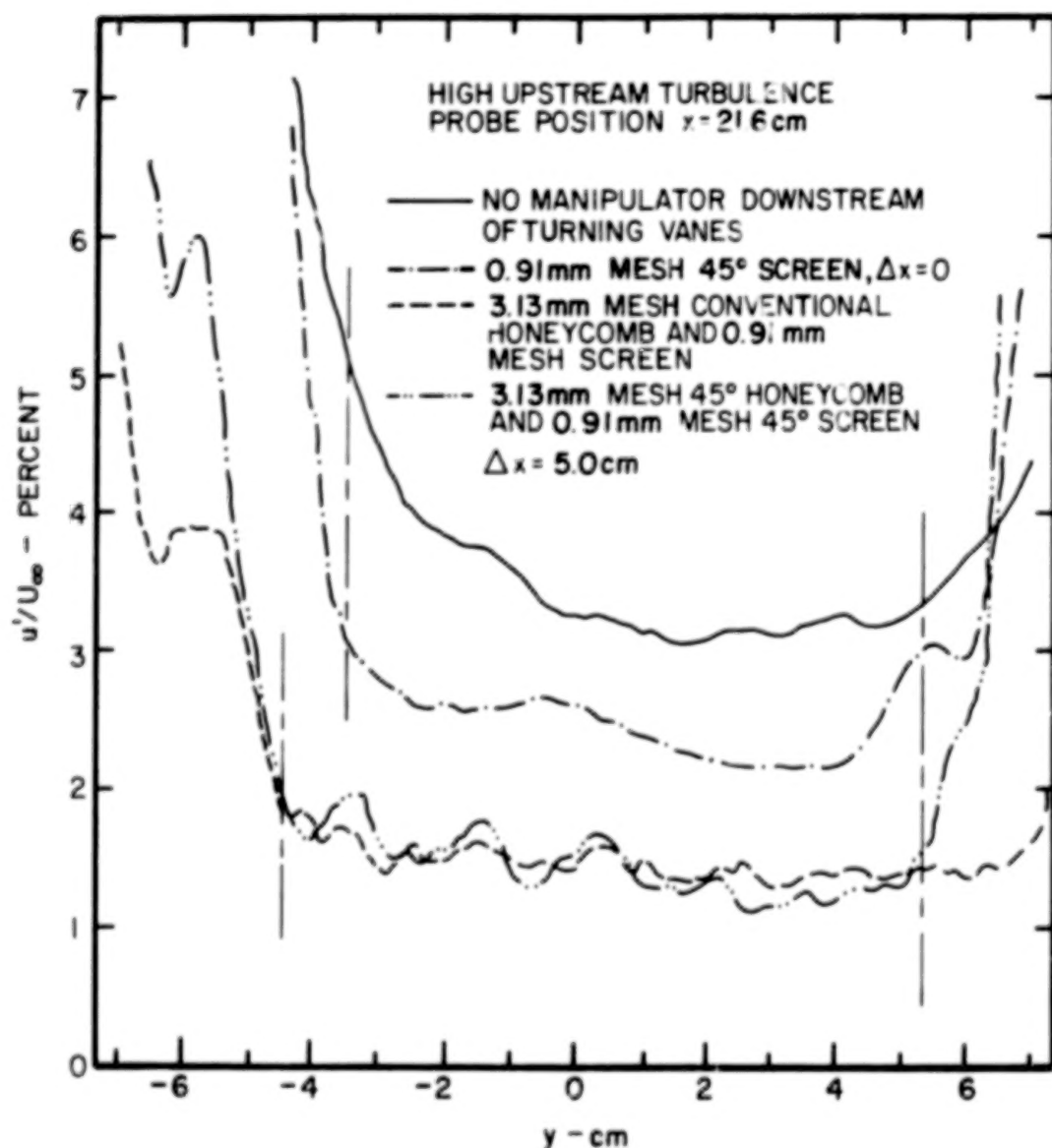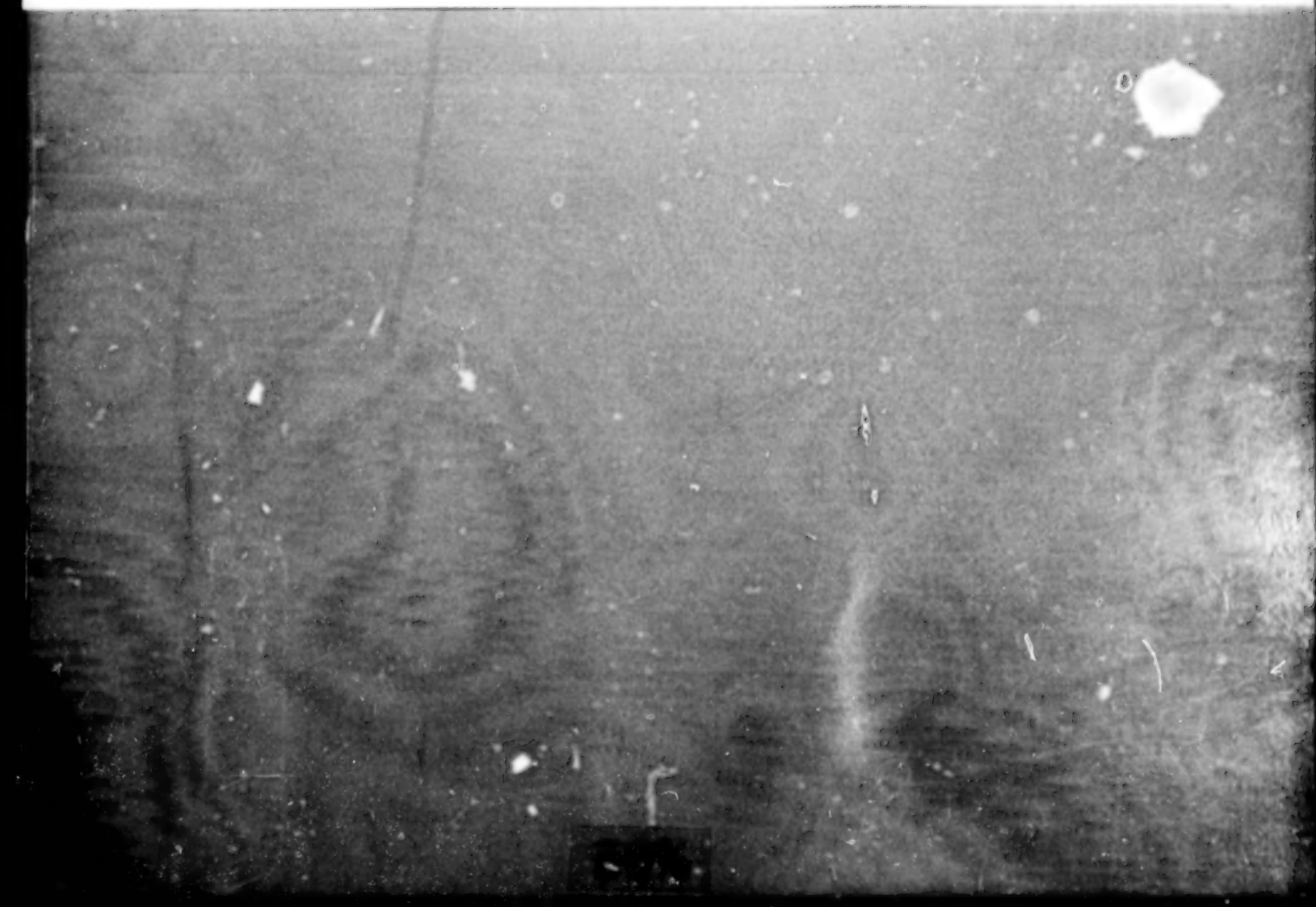
Figure 16. Effect of using no manipulator, a 45°-screen, a conventional honeycomb-screen combination, and a 45° honeycomb-45° screen combination downstream of turning vanes on lateral profile of turbulence intensity in high turbulence flow condition

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15. Supplementary Notes

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Final Report

16. Abstract

The feasibility of using a "new-concept" 45°-honeycomb for improving the flow quality in wind tunnels was investigated. This type of flow manipulator is particularly useful in wind tunnels which have either a short or no settling chamber and where it can increase the turbulence decay distance between the flow manipulators' assembly and the start of the contraction. The results of the experiments indicate that the turbulence levels in a wind tunnel using the 45°-honeycomb would be comparable to those obtainable using a conventional honeycomb, i.e., a honeycomb which is positioned normal to the mean flow in the settling chamber. However, this is true only when a 45°-screen is mounted immediately downstream of the honeycomb, and when some distance is provided between the trailing edges of the corner turning vanes and the upstream side of the 45°-honeycomb. This distance is required for adequate decay of the turning-vane wakes, thereby providing a reasonably uniform mean flow entering the honeycomb. Our results demonstrate that this distance should be at least twice the spacing between the turning vanes. Even though the resulting turbulence intensity is the same downstream of both the 45° "new-concept" honeycomb and the conventional honeycomb, there would have to be a significant improvement in the test-section turbulence intensity using the 45° "new-concept" honeycomb to justify the additional expense in fabricating and installing this type of honeycomb. The decision on which to use will depend on the relative effect of the contraction on the turbulence entering the contraction in each case, for even though the turbulence intensity is the same for both cases, the scales at the start of the contraction are different. The effect this has on the efficiency of reducing the turbulence by the contraction is completely unknown at this time.

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